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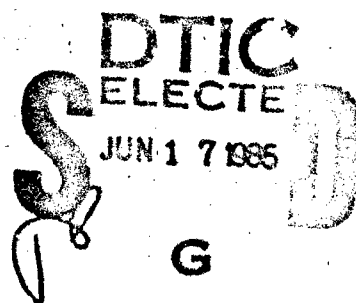200008140022

A practical guide to ionization chamber dosimetry at the AFRRI reactor

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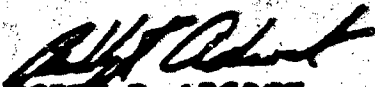BETHESDA, MARYLAND 20814-5145

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REVIEWED AND APPROVED

VINCENT L. McMANAMAN
CDR, MSC, USN
Chairman
Radiation Sciences Department

LAWRENCE S. MYERS, Ph.D.
Scientific Director

BOBBY R. ADCOCK
COL, MS, USA
Director

A PRACTICAL GUIDE TO IONIZATION CHAMBER DOSIMETRY AT THE AFRRI REACTOR

This manual was prepared by

Leon J. Goodman, Physical Scientist

National Bureau of Standards

Center for Radiation Research

Nuclear Radiation Division

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report provides the Armed Forces Radiobiology Research Institute (AFRRI) with practical guidance on the use of ionization chambers for performing mixed-field dosimetry at the TRIGA reactor. Experimental techniques, calculational formulas, physical constants, and correction factors are discussed, with emphasis on practice rather than theory in order to provide consistency and long-term continuity to the reactory dosimetry program at AFRRI. Keywords include: neutron radiation, gamma rays, kermas, radiation absorption, radiation dosage.

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Contents

1.0. Introduction

1.1. Purpose of Dosimetry Guide

This report was written to provide the dosimetrists at the Armed Forces Radiobiology Research Institute (AFRRI) with practical guidance on the use of ionization chambers in performing mixed-field dosimetry at the TRIGA reactor operated in a steady-state mode. A large part of the material presented is also applicable to dosimetry measurements made at other ionizing radiation facilities.

This dosimetry guide discusses the essential information needed to carry out ionization chamber measurements in the mixed neutron and gamma-ray fields produced at the reactor, and describes the practical aspects that are often neglected in formal treatises on dosimetry. Thus, the essential formulas needed to reduce the measured quantities to the required kermas or absorbed doses are presented without derivations, but the formulas and their various parameters are fully explained. Similarly, definitions of standard terminology, such as kerma or absorbed dose, are not given. However, the less familiar correction factors are discussed so that the reader will know not only what they are but also how to measure them and what magnitude of values to expect.

The thrust of this guide is to illuminate the practice rather than the theory of ionization chamber dosimetry. This approach has been adopted with the aim of providing consistency and long-term continuity to the reactor dosimetry program at AFRRI, particularly in consideration of the relatively frequent turnover of the scientific and technical staff.

1.2. Review of Contents

Following this Introduction, Section 2 discusses the general principles of mixed-field dosimetry, including where and how ionization chambers are calibrated and checked for proper operation. The calibration formulas are discussed in Section 3. Section 4 describes how measurements of neutron and gamma-ray kerma or absorbed dose are performed. The required formulas are presented and explained, but details on the required physical parameters and correction factors are deferred to Sections 5 and 6, respectively. Section 5 describes the needed physical parameters and gives their values for some of the routine irradiation configurations used at the reactor. The correction factors that need to be considered and possibly evaluated are discussed in Section 6. This section describes the methods used to measure these factors, and offers suggestions on which factors may be neglected or avoided by suitable measurement procedures. Finally, Section 7 offers advice on establishing and maintaining a reliable gas-flow system for the ionization chambers. The reference list is given in Section 9.

1.3. Supplementary Information

As mentioned above, this report does not give formula derivations or definitions of standard terminology used in radiation dosimetry. The author has assumed that the reader has at least some familiarity with the physical principles, quantities, and units used in ionization chamber dosimetry. For some readers this may be a poor assumption. To augment the information in this dosimetry guide, it is

recommended that the scientists and technical personnel making practical use of this guide acquire and become familiar with the following supplementary information (references 1-8) (Section 9 gives reference details):

Neutron Dosimetry for Biology and Medicine. This is Report 26 of the International Commission on Radiation Units and Measurements (ICRU), containing a wealth of information on neutron dosimetry. It is recommended as a primer for those who are new to this field.

Clinical Dosimetry for Neutrons. This ICRU Report is in preparation, and may become available in the latter part of 1985. It includes much information on the theory and practice of neutron dosimetry as applied to the therapeutic application of neutron beams of high energy in the clinical situation. Nevertheless, it is a useful reference for reactor dosimetry since it contains derivations and explanations of the formulas used in the present report.

Radiation Quantities and Units. This is Report 33 of the ICRU, and contains a concise exposition of the terminology, quantities, and units used in radiation dosimetry. It is a valuable reference giving both verbal and mathematical definitions.

"European protocol for neutron dosimetry for external beam therapy," by Broerse et al. This journal paper presents detailed derivations and rationale for the formulas applied to the clinical use of fast neutron beams, and provides helpful information to supplement the present report. It was written for use by clinical neutron dosimetrists in the European community.

Protocol for Neutron Beam Dosimetry. This report is similar
to the European protocol but was written by a task group of
the American Association of Physicists in Medicine (AAPM)
for use by clinical neutron dosimetrists in the United States.
It is presently available as AAPM Report 7, but it is under-
going revision and should be reissued in modified form in the
near future.

"Determination of absorbed dose and kerma in a neutron field
from measurements with a tissue-equivalent ionization
chamber," by Mijnheer and Williams. This journal paper also
presents the derivations and rationale for the formulas used
in the present report. It is recommended for its clear and
concise presentation of neutron dosimetry information.

"Calibration procedures of tissue-equivalent ionization cham-
bers used in neutron dosimetry," by Mijnheer and Williams.
This paper, in a report of the International Atomic Energy
Agency, also gives many formulas and derivations applicable to
neutron dosimetry, and presents an analysis of the uncertain-
ties involved in different calibration methods.

Ion Chambers for Neutron Dosimetry. This monograph is based
on reports presented at a 1979 workshop of the Commission of
the European Communities. It reviews the status of ionization
chambers used for neutron dosimetry. In addition to discus-
sions of the characteristics of a variety of ionization cham-
bers (including those available from two commercial vendors),
the report also has discussions on calibrations, corrections,
cavity chamber theory, physical constants, and experimental
techniques. It is recommended as a source for detailed,
practical chamber data.

2.0. General Principles of Mixed-Field Ionization Chamber Dosimetry

2.1. Instrument Selection and Use

In principle, any of several instruments or combinations of instruments can be used for neutron dosimetry, including ionization chambers, calorimeters, proportional counters, and instruments for the measurement of fluence and spectral data. This report discusses only the use of a pair of ionization chambers for determining neutron and gamma-ray kermas and absorbed doses. Reference 1 should be consulted for information on other suitable instruments and methods.

Neutron dosimetry is more complex than gamma-ray dosimetry, mainly because neutron fields always contain gamma rays produced by the source and by field-defining structures, by the irradiation environment, and by the irradiated object itself. Because neutrons can have a different biological effect compared to an equal absorbed dose of gamma rays, it is necessary to report the separate values of these two components. With ionization chambers this requires the use of the two-dosimeter method. One of the chambers is constructed of A-150 tissue-equivalent (TE) plastic, and it uses a steady flow of methane-based TE gas through the cavity. This instrument, referred to as the TE-TE chamber, has approximately the same response to neutrons and to gamma rays. Details of the wall and gas compositions are given in Appendix B of reference 1.

The second chamber is constructed with magnesium walls, and uses a steady flow of argon gas. This instrument will be referred to as the Mg-Ar chamber, and its response to neutrons is much less than its response to gamma rays. The use of a graphite chamber with carbon

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dioxide gas is deprecated because of the higher relative neutron response (see Section 5.9) of this wall and gas combination, and because the porosity of graphite makes it difficult to maintain gas purity without excessively high flow rates. A photon energy-compensated Geiger-Müller (GM) dosimeter is often used as the second dosimeter. However, experience has shown that in the exposure rooms of the AFRRI reactor the ambient gamma-ray background is usually excessive relative to the high gamma-ray response of the GM dosimeter.

Two or more ionization chambers may be arranged laterally to the radiation direction for simultaneous measurements. A few centimeters of separation between chambers having volumes of a few cubic centimeters or less should suffice to make interchamber radiation scatter negligible. The chambers should be oriented so that their axes are perpendicular to the radiation direction since this will best define the location of the center of the cavity volume with respect to the radiation source. After the chambers have been mounted, the gas flow adjusted, and the collecting potential applied, sufficient time should be allowed for transient phenomena to subside before beginning measurements. This practice should be followed whenever a chamber is disturbed by repositioning, adding or removing a chamber cap, or changing the applied voltage. The chamber may be considered to be stable when the electrometer response in the absence of radiation is fairly constant and does not exceed a few percent of the anticipated radiation response. Charge integration during irradiation should be performed long enough to obtain an electrometer reading that is large with respect to system instabilities. It is good practice to make several measurements in succession to evaluate the response variance. Charges measured before

and after the chamber is irradiated should be integrated for the same time as used during irradiation so as to provide an assessment of the compensation required to compute the net charge accumulated during irradiation.

2.2. Ionization Chamber Calibration

This section discusses the general procedure for maintaining ionization chamber calibrations that are traceable to a national standard, and the procedures for routine verification of proper chamber operation. The formulas needed to apply the chamber calibrations to neutron dosimetry are presented in Section 3.

2.2.1. Calibration at NBS or ACL. It is recommended that a chamber be designated as the AFRRI transfer standard chamber and that this instrument be used only for transferring the calibration from the standards laboratory to the ^{60}Co calibration source at AFRRI. The procedure for using such a transfer standard chamber is as follows. The chamber is flushed with air and then left open to the ambient atmosphere. It is irradiated at AFRRI in a fixed and reproducible arrangement and its response is recorded along with the ambient temperature and pressure. The irradiation source may be either a specially designed check source or the ^{60}Co gamma-ray machine that will be later used for calibrations of other dosimeters.

The chamber is then transported to the National Bureau of Standards (NBS) or to an AAPM Accredited Dosimetry Calibration Laboratory (ADCL) for calibration in a standard ^{60}Co beam. This measurement will be performed with the chamber open to atmospheric air, and will be in terms of the exposure or air kerma required to produce unit response

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from the chamber, i.e., roentgen per coulomb of charge collected (expo-sure) or grays per coulomb of charge collected (air kerma). When the chamber is returned to AFRRI, it should first be irradiated in the fixed check-source field to verify that the trip to and from the standards laboratory has not changed the chamber's response. Assuming that the result of this second check-source measurement is satisfactory, the transfer instrument is then used to determine the exposure rate or air kerma rate of the AFRRI ^{60}Co machine. The transfer instrument is then stored for future use to verify the ^{60}Co beam calibration periodically or when a problem is suspected.

2.2.2. Calibration at AFRRI. The procedure outlined in the previous subsection calibrates the gamma-ray beam from the ^{60}Co machine in terms of the exposure rate or air kerma rate at one or more well-defined positions in the beam. This calibrated beam is then used to calibrate other AFRRI chambers (with their usual cavity gases) used routinely for reactor dosimetry. These ^{60}Co chamber calibrations will be in terms of the exposure or air kerma required to produce unit response from the chamber, i.e., the same as for the transfer instru-ment. Such calibrations should also be preceded by and followed by a measurement with the check source. Section 3 discusses the conversion of these calibrations to the tissue absorbed dose calibration factor.

2.3. Calibration Verification

It is good practice to verify the proper operation of an ioni-zation chamber prior to its use for making mixed-field measurements. Two methods are described for making such checks.

2.3.1. <u>Verification With Check Sources</u>. Using check sources
to verify the calibration of an ionization chamber is a comprehensive
test since this method not only checks the integrity of the chamber, its
cables, and the electrometer, but also verifies the proper neutron and
gamma-ray response if a neutron and a gamma-ray source are used. Even
though the neutron source will also be a gamma-ray emitter, the response
of a TE-TE or a Mg-Ar chamber in the mixed field will serve to verify
that the gas in the TE chamber is TE gas and that the gas in the Mg
chamber is Ar (provided, of course, that the earlier check source data
used for comparison were obtained under appropriate conditions). The
check sources should be used in an arrangement that allows response
measurements to be made with a random uncertainty of 1% or less. It is
essential that a log sheet be maintained for each chamber, detailing its
history of calibrations and check source tests. Such records are
necessary for documenting a long-term drift or deterioration of chamber
response.

2.3.2. <u>Verification by Capacitance Measurement</u>. A simple and
quick method of verifying the integrity of a three-terminal chamber
(i.e., a guarded chamber), its cables, collecting potential supply, and
electrometer is by measuring the distributed capacitance between the
outer chamber wall (to which the collecting potential is applied) and
the inner collecting electrode. This is done as follows. With the
chamber connected to the electrometer system and a moderate collecting
potential applied, several measurements of drift charge are made using a
fixed time interval. The second step is to make several measurements of

the charge accumulated in the fixed time while applying a change in collecting potential, ΔV, during the charge accumulation time. This is done by ungrounding the electrometer input and then slowly changing the collecting potential at a rate so that ΔV has been applied before the fixed time has elapsed. When the fixed time is reached, the charge, ΔQ, induced into the collecting electrode by ΔV acting through the distributed capacitance C, is recorded. The collecting potential should be returned to the same initial value and the system allowed to stabilize before each repeat measurement is made.

The final step is to make several more measurements of drift charge in the fixed time interval. The drift charges measured before and after the ΔV charge measurements are then averaged and subtracted from the charges induced by the ΔV changes. The capacitance is then computed as $C = \Delta Q / \Delta V$, where ΔQ is the net drift-compensated change in charge corresponding to the voltage change ΔV. The magnitude of ΔV should be one that will produce a ΔQ with a small random uncertainty, and the fixed time over which each of the measurements is made should be chosen such as to allow the voltage to be changed at a moderate rate. For example, for a 0.5-cm^3 thimble chamber having $C = 0.7$ pF, the initial potential can be set at 400 V with $\Delta V = 100$ V, the fixed time being 30 s.

These capacitance check measurements should be repeatable on the order of 1% between different measurement sessions. It is recommended that a log sheet of capacitance measurements be maintained for each chamber. This may help in identifying a chamber that is undergoing long-term dimensional changes.

3.0. Calibration Formulas

3.1. Volume Calibration

It is possible to derive the radiation calibration of an ioni-
zation chamber from detailed knowledge of the cavity volume, chamber
materials, and various physical parameters. The difficulty arises in
knowing accurately the effective cavity volume in which ion production
and collection take place. Even for the relatively simple geometry of a
parallel-plate chamber, the field distortion present in the region of
the guard electrode complicates a straightforward computation of the
effective cavity volume. The usual resolution to this problem is to
calibrate the chamber in a gamma-ray field of known exposure rate and to
use these data to derive the mass of cavity gas and hence its volume.
Details and formulas for such computations are given in references 4
through 7.

3.2. Radiation Sensitivity Calibration

Dosimetrists generally ignore the computation of chamber
cavity volume and instead focus their attention on deriving the tissue-
absorbed-dose calibration factor, α_c, which is the quotient of the
absorbed dose in tissue adjacent to the cavity of the chamber by the
corrected chamber response. It is defined as

$$\alpha_c = \frac{X_c}{R_c} (f_t)_c \frac{(\Pi k_A)_c}{(\Pi k_R)_c} \qquad (1)$$

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where the ratio X_c/R_c is the exposure calibration in which X_c is the exposure at the geometric center of the chamber in the absence of the chamber, and R_c is the chamber response. The subscript c denotes the calibration radiation field. The conversion factor, which converts exposure to tissue-equivalent absorbed dose, $(f_t)_c$, is discussed in Section 5.2.

During 1985 NBS and the ADCL's will begin to supply air kerma calibrations in addition to exposure calibrations, which later will be discontinued. This change to $(K_{air})_c/R_c$ for the air kerma calibration will require that $(\bar{f}_t)_c$ in equation 1 be changed to an air kerma-to-tissue absorbed dose factor, $(f'_t)_c$, as discussed in Section 5.2.

The product of several correction factors Πk_A compensates for small distortions of the radiation field when measurements are made with the chamber in free air, and is given by

$$\Pi k_A = k_w k_{st} k_{rn} k_{an} \tag{2}$$

where k_w is the chamber wall attenuation and scatter correction factor (Section 6.2).

        k_{st} is the stem-scatter correction factor (Section 6.4),

        k_{rn} is the radial nonuniformity correction factor (Section 6.5), and

        k_{an} is the axial nonuniformity correction factor (Section 6.6).

The product of several correction factors Πk_R converts the reading, R, taken from the electrometer, to the electric charge produced within an ideal cavity at a reference temperature and pressure, and is given by

$$\Pi k_R = k_{t,p} k_s k_e k_l k_p k_f k_h \tag{3}$$

where $k_{t,p}$ is the temperature and pressure correction factor (Section 6.1),

k_s is the saturation correction factor (Section 6.3),

k_e is the electrometer correction factor (Section 6.7),

k_l is the leakage correction factor (Section 6.8),

k_p is the polarity correction factor (Section 6.9),

k_f is the gas flow-rate correction factor (Section 6.10), and

k_h is the humidity correction factor (Section 6.11).

This may appear to be a formidable list of correction factors, but (as discussed in Section 6) many of these factors can be either neglected or included in the method of making the measurements. Note that in equation 1 the two correction factor products have the subscript c, indicating that these factors are to be evaluated for the calibration radiation field.

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4.0. Mixed-Field Measurements

4.1. Neutron and Gamma-Ray Kerma and Absorbed Dose

At a point in a mixed field where the neutron and gamma-ray tissue absorbed doses or kermas are D_n and D_γ, respectively, the relative responses of the two chambers are given by

$$R'_T = k_T D_n + h_T D_\gamma \qquad (4)$$

$$R'_U = k_U D_n + h_U D_\gamma \qquad (5)$$

where the subscript T refers to the TE-TE chamber and the subscript U refers to the Mg-Ar chamber. The coefficients k_T and k_U are the responses of each chamber to the neutrons in the mixed field relative to its response to the gamma rays used for the calibration, and h_T and h_U are the responses of each chamber to the gamma rays in the mixed field relative to its response to the gamma rays used for the calibration. Consequently, R'_T and R'_U are the readings of the two chambers in the mixed field relative to their responses to the gamma rays used for the calibration.

The separate absorbed doses are obtained by simultaneous solution of equations 4 and 5 to give

$$D_n = \frac{h_U R'_T - h_T R'_U}{h_U k_T - h_T k_U} \qquad (6)$$

$$D_\gamma = \frac{k_T R'_U - k_U R'_T}{h_U k_T - h_T k_U} \qquad (7)$$

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The relative gamma-ray responses h_T and h_U can be computed from

$$h = \frac{W_c}{W_\gamma} \frac{(s_{m,g})_c}{(s_{m,g})_\gamma} \frac{[(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_m]_c}{[(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_m]_\gamma} \tag{8}$$

where c   denotes the calibration gamma rays,

    γ denotes the mixed-field gamma rays,

    t   denotes tissue,

    m   denotes wall material,

    W   is the average energy required to produce an ion pair in the cavity gas (Section 5.3),

    $s_{m,g}$ is the wall-to-gas restricted collision mass stopping power ratio, commonly referred to as the gas-to-wall absorbed-dose conversion factor (Section 5.4), and

μ_{en}/ρ is the mass energy absorption coefficient (Section 5.6).

The values of h_T and h_U are close to unity, and the simplifying assumption $h_T = h_U = 1$ is usually made. This is equivalent to assuming that the effective quality of the gamma rays in the mixed field is equivalent to the quality of the gamma rays used for the calibration with respect to the values of W, $s_{m,g}$ and μ_{en}/ρ. Equations 6 and 7 may then be simplified to

$$D_n = \frac{R'_T - R'_U}{k_T - k_U} \tag{9}$$

$$D_\gamma = \frac{k_T R'_U - k_U R'_T}{k_T - k_U} \tag{10}$$

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The relative neutron response k_T of the TE-TE chamber is computed in a manner similar to that used for h_T. Thus

$$k_T = \frac{W_c}{W_n} \frac{(s_{m,g})_c}{(r_{m,g})_n} \frac{[(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_m]_c}{(K_t/K_m)_n} \qquad (11)$$

where the subscript n denotes the mixed field, $r_{m,g}$ is the gas-to-wall absorbed-dose conversion factor for the non-Bragg-Gray cavity conditions generally produced by neutrons (Section 5.5), and $(K_t/K_m)_n$ is the ratio of neutron kerma in tissue to the neutron kerma in the chamber materials (Section 5.7).

Due to the lack of data for the wall and gas materials of the Mg-Ar chamber, the value of k_U cannot be readily computed, so it is usually evaluated by experimental methods (Section 5.9).

The relative chamber responses R_T' and R_U' are computed from the reading, R, obtained for each chamber in the mixed field.

$$R' = R\alpha_c \frac{(\Pi k_R)_n}{(\Pi k_A)_n} (k_d)_n \qquad (12)$$

The two products of correction factors Πk_R and Πk_A are defined the same as in equations 2 and 3 except that the subscript n in equation 12 indicates that the factors are to be evaluated for the mixed field. When equations 9 and 10 are solved for the tissue kermas in free air, then $(\Pi k_A)_n$ should be evaluated. When these equations are used to obtain the absorbed doses in a phantom, then $(\Pi k_A)_n$ is set to unity.

The displacement factor $(k_d)_n$ corrects for the perturbation produced by the chamber gas cavity when measurements of absorbed dose are made in a phantom. If we set $(k_d)_n = 1$, then the computed absorbed doses will be at the effective center of the chamber rather than at its geometric center. Section 5.8 discusses suitable values of this factor for phantom measurements. For tissue kerma determinations in free air, the displacement factor is unity.

Equation 10 sometimes will yield a negative value for D_γ, particularly when the gamma-ray kerma or absorbed dose is small relative to D_n, say a few percent. This is, of course, a physical impossibility. Assuming that the chamber responses have been measured accurately, a negative value of D_γ usually indicates that the value of k_U used is too large. Values of k_U are determined only approximately by experiment, and even then they apply only to the specific chamber configuration and radiation field used.

More puzzling is the rare occasion when equation 9 yields a computed value of D_n that is negative. This can occur in a radiation field containing only a small neutron kerma or absorbed dose relative to D_γ. Equation 6, which gives the relationship for D_n before the simplifying assumption $h_T = h_U = 1$ was made, shows that D_n depends on h_T and h_U; and it can be concluded that the simplifying assumption used to derive equation 9 is invalid if $D_n < 0$. It would be necessary to have spectral data for the gamma-ray component of the mixed field in order to evaluate the relative gamma-ray responses h_T and h_U of the two chambers using equation 8.

4.2 Total Kerma or Absorbed Dose

The total tissue kerma or absorbed dose, D_T, can be obtained simply by summing the two components computed from equations 9 and 10, i.e.,

$$D_T = D_n + D_\gamma \qquad (13)$$

An alternative is the simple expression

$$D_T = \frac{R_T'}{k_T} \, \frac{1}{1+\delta} \qquad (14)$$

where

$$\delta = \frac{D_\gamma}{D_T} \, \frac{h_T - k_T}{k_T} \qquad (15)$$

Now, since $k_T \approx 0.95$ and h_T is close to 1, if $D_\gamma/D_T < 0.4$ then we will have $\delta < 0.021$. Thus, in equation 14 if we set $\delta = 0$, then an error of less than about 2% will be made in computing D_T, i.e.,

$$D_T \approx \frac{R_T'}{k_T} \quad \text{for} \quad \frac{D_\gamma}{D_T} < 0.4 \qquad (16)$$

Table 1 lists the errors produced in computing D_T from equation 14 when it is assumed that $\delta = 0$. Even for $D_\gamma/D_T = 1$, the error does not exceed 5% as a consequence of setting $k_T = 0.95$. A potentially more serious error in this case might be the failure to realize that D_T does not contain a component of absorbed dose due to neutrons.

Table 1. Errors produced in computing D_T from equation 14 by assuming $\delta = 0$*

D_γ / D_T	D_n / D_γ	% error in D_T
0.02	49	0.1
0.05	19	0.3
0.1	9	0.5
0.2	4	1.0
0.3	2.3	1.6
0.4	1.5	2.1
0.6	0.67	3.1
0.8	0.25	4.0
1.0	0	5.0

*For this table, $k_T = 0.95$ and $\lambda_T = 1.00$ were used.

When $D_\gamma / D_T = 1$, i.e., $D_n = 0$, equation 14 reduces to

$$D_\gamma = R_T' / h_T \tag{17}$$

which is the same result as given by equation 4 with $D_n = 0$.

D_γ in a mixed field can be evaluated from equation 5, with the assumption $h_u = 1$, as

$$D_\gamma = R_u' - k_u D_n \tag{18}$$

If the low values of k_U for a small Mg-Ar ionization chamber are considered (as shown in Table 2, page 23), then it is possible to make the following approximation with an error of less than 2%:

$$D_\gamma \approx R_U' \quad \text{for} \quad \begin{array}{l} D_n / D_\gamma < 2, \text{ 6 inches of Pb-shielded reactor;} \\ D_n / D_\gamma < 1, \text{ bare reactor;} \\ D_n / D_\gamma < 0.8, \text{ 12 inches of water-shielded reactor.} \end{array} \qquad (19)$$

It may be useful to note that (see also Table 1)

$$\frac{D_n}{D_\gamma} = \frac{D_T}{D_\gamma} - 1 \qquad (20)$$

Equation 16 can be used to approximate D_T from measurements made with only a TE-TE chamber, and equation 19 can be used to approximate D_γ from measurements made with only a Mg-Ar chamber. These approximations are useful for making quick dosimetry evaluations or when more complete data are not available. However, the errors in these approximations are not random, and they result in errors that make D_T or D_γ systematically too high. It is recommended that the final dosimetry evaluations be made without these errors by using equations 9 and 10.

Table 2. Values of physical parameters for three shielding configurations used in Exposure Room 1 of the AFRRI reactor (reference 19)

Parameter	Shielding Configuration		
	6" Pb [*]	Bare [†]	12" H_2O [■]
$\bar{E}_n$ [§]	0.45	0.8	1.55
W_n, [‖] MTE [¶] gas	32.2	32.0	31.7
W_n/W_c [**]	1.099	1.092	1.082
K, [††] ICRU muscle	1.52	1.96	2.76
K, A-150 plastic	1.54	2.02	2.83
K, MTE gas	1.54	2.00	2.80
k_U, Mg-Ar	0.01	0.02	0.025
κ_U, GM	0.002	0.0016	0.0027

[*] Reactor core shielded with 6 inches of Pb

[†] Bare reactor room, i.e., no added shielding

[■] Reactor core shielded with 12 inches of water

[§] Tissue-kerma-weighted mean neutron energy in MeV

[‖] W_n is in units of eV.

[¶] MTE denotes methane-based TE gas.

[**] W_c = 29.3 eV.

[††] Kerma factors are in units of 10^{-11} Gy cm^2.

5.0. Physical Parameters

5.1. Spectral Information

The items discussed in the following subsections as physical parameters are quantities whose values are usually obtained either directly or by computation from previously published or otherwise available data. The evaluation of these physical parameters generally requires knowledge of the radiation spectrum for which the parameter is to be computed. In some cases only rough radiation quality information is needed, whereas other cases require use of a reliable and detailed spectrum. Table 2 gives the tissue-kerma-weighted mean neutron energies for three reactor configurations. The data presented in Table 2 were computed using neutron and gamma-ray spectral data from reference 9.

5.2. Exposure- and Air Kerma-to-Tissue Absorbed Dose Conversion Factors, $(f_t)_c$ and $(f'_t)_c$

The factor $(f_t)_c$ required to convert exposure to tissue-absorbed dose for computing the calibration factor, α_c, is defined as

$$(f_t)_c = \frac{(W_{air})_c}{e} \left[\frac{(\mu_{en}/\rho)_t}{(\mu_{en}/\rho)_{air}} \right]_c \tag{21}$$

where subscript c denotes the calibration radiation quality, subscript t denotes tissue, and e is the electronic charge. For dry air and ICRU muscle or soft tissue, $(f_t)_c$ = 37.3 J/C or $(f_t)_c$ = 9.62 × 10^{-3} Gy/R for either ^{60}Co or ^{137}Cs in air (reference 10).

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The factor $(f_t')_c$ required to convert air kerma to tissue absorbed dose for computing the calibration factor, α_c, is defined as

$$(f_t')_c = \left[\frac{(\mu_{en}/\rho)_t}{(\mu_{en}/\rho)_{air}}\right]_c [1 - g]_c \qquad (22)$$

where g is the fraction of charged-particle kinetic energy lost to bremsstrahlung in the material. For ^{60}Co and ^{137}Cs gamma rays, the ratio of the mass energy-absorption coefficients is 1.102 for either ICRU striated muscle or ICRU soft tissue (reference 11). For ^{60}Co and ^{137}Cs gamma rays, the fraction g is 0.003 and 0.001, respectively (reference 12). With these values, equation 22 yields $(f_t')_c = 1.099$ for ^{60}Co in air, and $(f_t')_c = 1.101$ for ^{137}Cs in air.

5.3. Average Energy Required to Produce an Ion Pair, W

The basic quantity measured with an ionization chamber is the electric charge or current produced in the gas cavity. To obtain the kerma or absorbed dose, this quantity is converted to energy by the use of W, the average energy required to produce an ion pair in the gas. For the electrons produced by the energetic gamma rays used for calibration, i.e., ^{60}Co, a value of $W_c = 29.3$ eV is appropriate for methane-based TE gas (reference 13).

Values of W_n for the secondary particles produced in methane-based TE gas by neutrons are given in reference 13, which also describes the method of calculating W_n for a known neutron spectrum. Table 2 lists computed values of W_n and W_n/W_c for three reactor configurations.

5.4. Wall-to-Gas Stopping-Power Ratio, $s_{m,g}$

The wall-to-gas stopping-power ratio, $s_{m,g}$, applies when the ionization chamber can be considered to have a Bragg-Gray cavity. For ^{60}Co gamma rays and for the gamma rays present in the mixed field, $s_{m,g} = 1.00$ is a good assumption for the TE-TE chamber.

5.5. Gas-to-Wall Absorbed-Dose Conversion Factor, $r_{m,g}$

The gas-to-wall absorbed-dose conversion factor, $r_{m,g}$, applies to ionization chamber measurements of neutron fields for which the gas cavity contributes significantly to the secondary particle spectrum. Attempts to compute $r_{m,g}$ have yielded values that differ from unity by 1% or 2% and have uncertainties of about 2%. It is recommended that $r_{m,g} = 1.00$ be used for neutron measurements with the TE-TE chamber.

5.6. Mass Energy-Absorption Coefficient Ratio, $(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_m$

Because of the good simulation of ICRU muscle or soft tissue by the TE-TE chamber for ^{60}Co gamma rays and for the gamma rays present in the mixed field, it is recommended that $(\mu_{en}/\rho)_t/(\mu_{en}/\rho)_m = 1.00$ be used for the mass energy-absorption coefficient ratio.

5.7. Neutron Kerma-Factor Ratio, $(K_t/K_m)_n$

Neutron kerma factors, i.e., the c·ients of kerma by fluence, are given for a variety of elements, compounds, and mixtures in reference 14. These values can be used to derive suitably weighted mean kerma factors using data on the neutron spectrum at the measurement position. For the relatively low energy neutrons present in reactor spectra, the chamber kerma is due to both the wall and gas materials.

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Since the wall and gas compositions of the TE-TE chamber are very similar, it is satisfactory to use the average of the wall and gas kermas for the kerma in the chamber material, K_m. Kerma factors for ICRU muscle tissue, A-150 plastic, and methane-based TE gas are listed in Table 2 for three reactor configurations. Spectrum changes as a neutron beam passes into a tissue phantom will probably have little effect on the kerma-factor ratio.

5.8. Displacement Factor, $(k_d)_n$

The displacement factor, $(k_d)_n$, corrects the measured ionization charge or current to compensate for the differences in attenuation and scattering of the primary radiation caused by the displacement of phantom material by the ionization chamber cavity. Thus the charge or current is obtained that would have been measured by a hypothetical chamber of zero volume centered at the same location. For high-energy neutrons, $(k_d)_n$ can be 1% or 2% less than unity. However, for the low-energy neutrons produced by the reactor, experiment has shown that $(K_d)_n = 1.00$ is a good approximation (reference 15).

5.9 Relative Neutron Response, k_U

In principle, the relative neutron response, k_U, for the Mg-Ar chamber can be calculated using an equation similar to equation 11. However, calculations of k_U have large uncertainties due to the uncertainties of the parameters needed for computation. Thus, values of k_U are usually obtained by a variety of experimental methods. Reference 16 gives values of k_U for a Mg-Ar chamber, and reference 17 gives k_U values for a GM dosimeter. Since k_U is a function of neutron energy, these data must be appropriately weighted to derive values of k_U applicable to neutron fields with known spectra. Table 2 gives k_U values for a Mg-Ar chamber and a GM dosimeter for three reactor configurations.

6.0. Correction Factors

The correction factors discussed in the following subsections are quantities whose values are usually determined by making measurements in specific arrangements of radiation source and instrumentation system.

6.1. Temperature and Pressure Correction Factor, $k_{t,p}$

All chamber readings have to be converted to a reference temperature and pressure, which are usually chosen to be those used by the standardizing laboratory at which the exposure chamber is calibrated. In the U.S. the reference values used by NBS and the ADCL's are 295.16 K (22°C) and one standard atmosphere (760 mm of Hg or 101.3 kPa). When the chamber cavity temperature and pressure for a measurement are T_m(°C) and P_m (mm of Hg), respectively, the correction factor is given by

$$k_{t,p} = \frac{273.16 + T_m}{295.16} \times \frac{760}{P_m} \qquad (23)$$

To keep uncertainties less than 0.1%, the thermometer should be capable of being read with an overall uncertainty of 0.3°C or less, and the barometer should be capable of being read with an overall uncertainty of 0.8 mm Hg or less. It is important to assure that the chamber, gas supply, and phantom temperatures are in equilibrium with the ambient temperature, and that the gas-flow rate is not so large as to cause the cavity pressure to be significantly greater than the atmospheric pressure (see Section 6.10).

6.2. Chamber Wall Attenuation and Scatter Correction Factor, k_w

When a TE-TE chamber is used to make absorbed dose measurements in a phantom, the chamber wall attenuation and scatter correction factor is $k_w = 1.00$. This factor also applies for measurements in a phantom with the Mg-Ar chamber, but in this case the magnesium wall should be thick enough to stop the most energetic recoil protons generated in the hydrogenous phantom material. This factor, however, must be evaluated when chamber measurements are used to derive tissue kerma in free air since such a determination implies that the radiation is neither attenuated by the chamber wall nor augmented by scatter from the chamber wall. First, it is important to establish that the chamber wall, plus a buildup cap if needed, is of adequate thickness to assure that transient secondary-particle equilibrium is attained in the chamber for the kerma measurement. Measurements must then be made by adding caps to the chamber to assess the effect of further increases in wall thickness.

In general, attenuation is dominant over scatter, and increasing wall thickness decreases chamber response. A graph of response versus wall thicknesses beyond that required to produce secondary particle equilibrium is extrapolated to zero wall thickness, and k_w is computed as the ratio of the response obtained with the wall thickness usually used to the response obtained by the extrapolation to zero wall thickness. Strictly, the extrapolation should be made to the mean center of charged-particle production; however, for the low-energy neutrons at the reactor, this center is very close to the inner wall of the chamber so that extrapolation to zero wall thickness is an acceptable procedure. The factor k_w is usually on the order of a few percent less than unity, depending on the actual wall thickness used for the measurement of tissue kerma in free air and on the radiation quality.

6.3. Saturation Correction Factor, k_s

The electric charge measured with an ionization chamber is less than the charge liberated in the chamber cavity by the directly ionizing particles due to initial (intratrack) and general (intertrack) ion recombination. Tests to determine the ionization saturation correction factor, k_s, should be made using an absorbed dose rate and radiation field the same as or similar to that for which dosimetry is required. The tests consist of making response measurements with several values of collecting potential. One voltage polarity may be used for all the measurements, but use of both polarities for each voltage will increase the precision and reliability of the data. Using reciprocal response and voltage quantities, these data are extrapolated to infinite voltage (reference 18). For neutrons, initial ion recombination usually dominates, and a plot of R^{-1} against V^{-1} will enable k_s to be evaluated as the ratio of R at $V^{-1} = 0$ to R at the potential used to make the kerma or absorbed dose measurements. Typically, $1 < k_s < 1.01$.

At high absorbed dose rates, general recombination may dominate and then a plot of R^{-1} against V^{-2} is appropriate for performing the extrapolation. For some intermediate cases it may be necessary to fit the data to a function of both V^{-1} and V^{-2} to make a reliable extrapolation.

Although this dosimetry guide is not intended to cover dosimetry for reactor pulses, it is appropriate to remark that the main problem in performing such measurements with ionization chambers is the difficulty of accurately accounting for the large amount of general ion recombination that occurs in this mode of reactor operation. Calorimetric

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dosimetry is recommended for this situation, and could be used to assess the saturation correction factors for ionization chambers. However, this approach must be used with caution since these factors will depend on the pulse intensity, duration, and shape. Large factors, say greater than 5%, are acceptable, provided that the pulse characteristics do not vary significantly.

6.4. Stem-Scatter Correction Factor, k_{st}

For measurements in a phantom, the stem-scatter correction is k_{st} = 1.00. When measurements are made to determine tissue kerma in free air, the effect of stem scatter is to augment slightly the chamber response. The stem-scatter correction factor can be assessed by placing a dummy stem on the chamber end opposite to the functional stem, and measuring the charge produced relative to the charge produced without the dummy stem. The value of k_{st} is then the ratio of the response with the dummy stem to that without the dummy stem. Typically $1 < k_{st} < 1.01$, and it is often difficult to attain the precision required for its determination. Since k_{st} is close to unity and has about the same value for the calibration and mixed radiation fields, an acceptable procedure is to neglect stem scatter for both measurements, i.e., assume k_{st} = 1.00.

6.5. Radial Nonuniformity Correction Factor, k_{rn}

If the radiation field in the plane perpendicular to the axis of the beam is not uniform, it may be necessary to apply a correction factor k_{rn} for this radial nonuniformity. In most calibration and measurement situations, k_{rn} = 1.00.

6.6. Axial Nonuniformity Correction Factor, k_{an}

Most measurements are made with the ionization chamber at a large enough distance from the radiation source so that there is no appreciable variation in kerma averaged over the axial extent of the chamber relative to the kerma at the center of the chamber. If the distance from the source to the chamber center is ten or more times the chamber radius, the use of k_{an} = 1.00 will be in error by less than 0.3% (reference 19).

6.7. Electrometer Correction Factor, k_e

The electrometer correction factor, k_e, relates the reading of the electrometer to the actual charge generated. If the same electrometer is used for the calibration and for the measurements in the mixed field, then the absolute accuracy of the electrometer is of no consequence, and k_e = 1.00. When different electrometers are used, either they should be adjusted to measure charge accurately or their relative calibrations should be measured to assess k_e.

6.8. Leakage Current Correction Factor, k_l

Electrometers, cables, and ionization chambers should not have significant leakage current relative to the charges or currents to be measured. Electrometer drifts due to system instabilities or to ambient background radiation have the same effect as a leakage current; i.e., they increase or decrease the chamber response. An efficient method of taking such drifts into account is to make several drift

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measurements before and after the measurements of the radiation field are made, and then to add or subtract the average drift to the measured charge produced by the radiation so as to compute a net charge. When this is done, $k_1 = 1.00$.

6.9. Polarity Correction Factor, k_p

A change in the polarity of the collecting potential can cause a change in the absolute value of the measured charge. Experience has demonstrated that measurements in Exposure Room 1 of the AFRRI reactor produce polarity effects that can be as much as 20% to 30% at large distances (> 3 m) from the reactor core. These differences are probably due to extra-cameral currents, and their effect can be essentially eliminated by making several measurements at both polarities and using the average response. If this procedure is followed, $k_p = 1.00$.

6.10. Gas Flow-Rate Correction Factor, k_f

It is possible to assess experimentally the variation in chamber response with gas flow rate. Diffusion of air into the chamber cavity is significant at low flow rates, and pressure buildup in the cavity is significant at high flow rates. Between these extremes there usually exists a broad plateau of uniform response not significantly dependent on flow rate. Operation of the chamber in this range of flow rates allows us to set $k_f = 1.00$. For the 0.5 cm^3 Exradin ionization chamber, this range of flow rates is from about 10 to 100 cm^3 min^{-1}. A good approach is to always use the same flow rate, say 30 cm^3 min^{-1}.

6.11. Humidity Correction Factor, k_h

For a chamber flushed with TE gas or argon, the humidity correction factor is $k_h = 1.00$. A humidity correction may be made for an air-filled chamber open to the atmosphere when the standardizing laboratory provides a calibration factor for the exposure standard chamber for dry air. Reference 20 gives a curve of k_h^{-1} as function of relative humidity which shows that k_h differs from unity by 0.3%, at most. In the United States, standardizing laboratories provide calibration factors for ambient air, so that $k_h \neq 1.00$.

6.12. Summary of Correction Factors

The foregoing subsections have discussed 11 correction factors; however, only $k_{t,p}$ and k_w are usually large enough to require careful evaluation. The other factors can be either neglected, determined approximately, or set equal to 1.00 by suitable measurement procedures. Thus, the evaluations of ΠK_A and ΠK_R are rendered much less formidable. It is recommended that records be kept of these correction factors as they are evaluated for specific chambers and radiation fields, so that they will be available for future use.

As examples and for future reference, Table 3 lists correction factors for two commercially available models of ionization chambers[*] irradiated in ^{60}Co beams and in AFRRI reactor fields. These factors were derived from measurements performed at NBS and at AFRRI.

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[*] In the interests of accuracy and clarity in describing various items of instrumentation, mention is made of commercial sources. This in no way implies endorsement of such products by the U.S. Government.

7.0. Gas Flow Systems

7.1. Static Gas Filling Versus Gas-Flow Systems

Sealed ionization chambers containing a static gas filling are sometimes used. For example, proportional counters can often be used over moderate time periods with a static gas filling. The ionization chambers routinely used at the AFRRI reactor have too low a ratio of cavity volume to surface area for reliable operation as sealed instruments.

7.2. Gas Composition and Verification

It is prudent when procuring TE gas to request an analysis to ensure that the cylinder of gas obtained has a composition close to that desired, and that the components of the gas mixture have been thoroughly mixed. Commercial gas vendors mix the gas before a sample is taken for analysis. Once mixed, thermal diffusion will prevent the gas components from separating.

The acceptability of a TE gas mixture can be evaluated by computing the kerma factor for the analyzed composition using the data of reference 14. A deviation of a few percent from the kerma factors shown in Table 2 for methane-based TE gas is acceptable, and the small difference may be taken into account in the evaluation of the neutron kerma factor ratio as discussed in Section 5.7.

If the composition of gas on hand and in use becomes suspect, a sample of the gas can be drawn and analyzed. A gas sample may be obtained by connecting a suitable clean sample container to a gas manifold to which a vacuum pump, pressure gauge, and the gas supply cylinder

Table 3. Correction factors for two commercially available ionization chambers (Exradin model T2 with TE cavity gas and Exradin model MG2 with argon cavity gas) irradiated in ^{60}Co beams and in AFRRI ER1 reactor fields

Chamber and Radiation	Correction Factors		
	k_w	k_s [S]	k_{st}
Model T2			
^{60}Co	0.992 [I]	1.001	1.008
6" Pb [*]	0.984	1.002	-
Bare [†]	0.976 [¶]	1.002	-
12" H$_2$O [■]	0.995 [**]	1.002	-
Model MG2			
^{60}Co	0.992 [I]	1.009	1.009
6" Pb [*]	0.988	1.006	-
Bare [†]	0.986 [I]	1.006	-
12" H$_2$O [■]	0.964 [**]	1.006	-

[*] At 1 m from nominal center of reactor core with 6 inches of Pb shielding

[†] At 1 m from nominal center of reactor core with no added shielding

[■] At 1 m from nominal center of reactor core but with core displaced so as to provide 12 inches of water shielding

[S] Factors with 400 V collecting potential

[I] Factor with 1-mm-thick cap of same material as chamber wall

[¶] Factor with 2-mm-thick cap of same material as chamber wall

[**] Factor with 5-mm-thick cap of same material as chamber wall

have been connected. All connections to the manifold should be made via shutoff valves, except for the gauge. The sample container, gauge, and manifold are evacuated and then filled with the gas several times to flush the r out of the system. Finally, the sample container is filled with the gas to an appropriate pressure and then isolated via its shutoff valve. In some cases it may be possible to transport the gas supply cylinder to the analysis laboratory, which will then have the responsibility of drawing the sample for analysis.

A quicker check of gas composition can often be made by using a neutron source, such as ^{252}Cf, to check the response of the chamber. This technique can reveal significant departures from the optimum hydrogen content of TE gas or the presence of hydrogenous contamination in argon.

7.3. Flow System Hardware

The valves, flow meter, tubing, and connectors that comprise the gas flow system should be chosen with care to achieve a reliable system that can be readily assembled and modified as needed. All joints should seal tightly to avoid leakage and waste of gas. Two systems of gas fittings that have been found to be versatile and reliable for use with ionization chambers are:

Gra-Tec, Inc., 156 North Plymouth Avenue, Rochester, New York 14608, telephone (716) 232-1180. Brass modular fittings are available in a large variety of adaptors and interconnections using rubber O-ring seals. Manifolds, valves, and starter kits are available for use with various sizes of tubing.

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Alltech Associates, Incorporated, Applied Science Labs, 2051 Waukegan Road, Deerfield, Illinois 60015, telephone (312) 948-8600. Teflon modular fittings designed for use in liquid chromatography are available for use with small-diameter (1/16- and 1/8-inch) teflon tubing.

The components available from the latter supplier are particularly suitable for use at and close to the chamber. Teflon tubing is recommended for lengthy connections rather than tubing of soft plastic or rubber.

7.4. Establishing and Checking Gas Flow

Section 6.10 discusses the rationale for choosing an appropriate gas-flow rate. Since low flow rates are required, only low gauge pressures above atmospheric pressure are needed from the pressure-reducing regulating valve at the gas cylinder. Gas flow should be started at a high flow rate to flush all tubing and the chamber cavity with the desired gas. After flushing for a time long enough to assure that only clean cylinder gas flows through the chamber, the flow rate should be reduced to the desired low rate as indicated by a gas-flow meter having adequate resolution to permit repeatable settings. Gas flow through the cavity can be verified by temporarily connecting one end of a short length of tubing to the gas exhaust port and observing the gas bubbles produced when the other end of the tube is placed in water. Care should be exercised to prevent any water or its vapor from being introduced into an argon gas system, since the response of a Mg-Ar chamber can be adversely affected by even small amounts of hydrogenous material.

Acknowledgment

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